

GALACTIC CONSTRAINTS ON CHAMPS

F. J. SÁNCHEZ-SALCEDO AND E. MARTÍNEZ-GÓMEZ

Instituto de Astronomía, Universidad Nacional Autónoma de México, Ciudad Universitaria, Apt. Postal 70 264, C.P. 04510, Mexico City, Mexico
Draft version December 3, 2008

ABSTRACT

We improve earlier Galactic bounds that can be placed on the fraction of dark matter in charged elemental particles (CHAMPs). These constraints are of interest for CHAMPs whose mass is too large for them to have seen through their electromagnetic interaction with ordinary matter, and whose gyroradius in the galactic magnetic field is too small for halo CHAMPs to reach Earth. If unneutralized CHAMPs in that mass range are well mixed in the halo, they can at most make up a fraction $\lesssim (3-7) \times 10^{-3}$ of the mass of the Galactic halo. CHAMPs might still be a solution to the cuspy halo problem if they decay to neutral dark matter but a fine-tuning is required. We also discuss the case where CHAMPs do not populate a spherical halo.

Subject headings: dark matter – galaxies: halos – galaxies: kinematics and dynamics – galaxies: magnetic fields

1. INTRODUCTION

Massive particles with integer electric charge (CHAMPs), denoted here by X , were considered as dark matter candidates in the late eighties (De Rújula et al. 1990; Dimopoulos et al. 1990; Gould et al. 1990; Chivukula et al. 1990). Although stable CHAMPs are predicted in some extensions of the standard model, astrophysical constraints plus bounds from underground detectors, from balloon experiments and the lack of detection of anomalous hydrogen in the sea water, basically rule out CHAMPs as dark matter (see Perl et al. 2001 and Taoso et al. 2008). In particular, the non-detection of heavy water in the sea excludes CHAMPs with masses between 10 and 10^4 TeV (Verlker et al. 1992). All the above constraints were derived for the standard flux of particles at Earth from the Galactic halo. If magnetic fields prevent the flux of CHAMPs to penetrate the Galactic disk, one must reevaluate earlier bounds (Chuzhoy & Kolb 2008).

Essentially all X^- should have bound to protons, forming neutraCHAMPs, which decouple from the photon-baryon fluid and drive structure formation prior to recombination. NeutraCHAMPs reach Earth unimpeded. Searches for neutraCHAMPs in cosmic rays rule out particles with masses between 100 and a few 10^4 TeV (Barwick et al. 1990). Nevertheless, heavy-water searches, cosmic rays searches, and constraints from overproduction of ^6Li (Berger et al. 2008) are only relevant if CHAMPs are singly charged, because for other charges, a CHAMP no longer behaves like a proton.

If a significant fraction of the mass of halos is made up by CHAMPs, it may have a strong impact on the observable Universe (e.g., Chuzhoy & Kolb 2008). It is therefore important to constrain the abundance of CHAMPs in galactic halos. After revising Galactic requirements for CHAMPs to be absent in the Galactic disk, we give an upper limit on the abundance of CHAMPs in the Galactic halo.

2. SHIELDING THE DISK WITH MAGNETIC FIELDS

While neutraCHAMPs have no difficulties to penetrate the Galactic disk and the solar wind to reach Earth, the penetration of unneutralized CHAMPs may be impeded by the presence of magnetic fields. Denote by ϵ the electric charge of CHAMPs in units of e , the elementary electron charge. For

$m_X > 10$ TeV and $\epsilon \leq 1$, CHAMPs in the Galactic halo behave as a collisionless plasma because the self-collision time is $> 10^5$ Gyr and the mean free path is $> 10^6$ kpc. Such a plasma consists of charged particles influenced only by gravity and electromagnetic fields. We will consider first the interaction of halo CHAMPs with the Galactic magnetic field.

It is well-known that when charged particles interact with a magnetized body, a boundary layer that divides two regions with different conditions is created (Parks 1991). Thus, charged particles will penetrate this boundary by some distance before they are turned around by the $\vec{v} \times \vec{B}$ force (Figure 1). The boundary layer is formed because of the partial penetration of the charged particles before they are deflected back. The orbits described by negative and positive charged particles in the neighborhood of the magnetic boundary are drawn in Fig. 1.

Since the Galactic magnetic field is not perfectly plane-parallel and has a nonzero turbulent component, i.e. $\vec{B} = \vec{B}_0 + \vec{b}$, where \vec{B}_0 is the regular (homogeneous) magnetic field and \vec{b} denotes the turbulent field, the particle motion is determined not only by the average magnetic field but also by scattering at field fluctuations, a stochastic process which requires the solution of transport equations with particle ensembles. Depending on the magnitude of these fluctuations, we distinguish between weak and strong turbulence which leads to different physical phenomena (Kallenrode 1998). Particle propagation in turbulent fields can be understood as a diffusive process, reason why we consider the spatial diffusion of *collisionless* halo CHAMPs into the galactic disk. The diffusion timescale τ_{diff} across the galaxy disk thickness H for a halo CHAMP, is bracketted in the range:

$$\frac{H^2}{2D_{\parallel}} < \tau_{\text{diff}} \lesssim \frac{H^2}{2D_{\perp}}, \quad (1)$$

where D_{\parallel} and D_{\perp} are the diffusion coefficients parallel and transverse to the mean component of the magnetic field, which is observed to be parallel to the disk. Within the disk, the magnetic field can be considered static because Alfvén waves propagate with velocities of the order of the Alfvén speed $v_A \sim 6 \text{ km s}^{-1}$, which is smaller than the typical velocities of CHAMPs $\sim \sqrt{3}v_X$, where $v_X \simeq 150 \text{ km s}^{-1}$ is the one-dimensional velocity dispersion for halo particles. The diffusion coefficients depend on the turbulence level

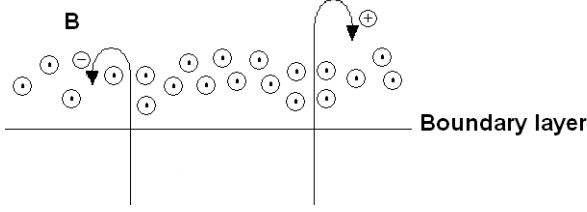


FIG. 1.— Structure of the magnetic boundary layer formed in the caps of galactic disks by the partial penetration of the charged particles before they are deflected back. We also illustrate the corresponding orbits of particles in the neighborhood of such boundary for both types of charge, that is, negative and positive.

$\eta \equiv (1 + \langle B_0^2 \rangle / \langle b^2 \rangle)^{-1}$, and on the rigidity $\chi \equiv 2\pi r_L / \lambda_{\max}$, with r_L the Larmor radius defined with respect to the total magnetic field and λ_{\max} the maximum scale of the turbulence $\sim H/2$ (Giacalone & Jokipii 1999; Casse et al. 2002). Observations of the Galactic polarized synchrotron background yield $1 < \langle b^2 \rangle / \langle B_0^2 \rangle < 9$ (Fletcher & Shukurov 2001, and references therein), implying that $0.5 < \eta < 0.9$. Since τ_{diff} scales as the inverse of the diffusion coefficients and those are essentially a monotonic function of η , we use $\eta \simeq 0.5$ in our estimate of D_{\perp} in order to give an upper limit on the diffusion timescale. Taking advantage of the numerical result by Casse et al. (2002) that $D_{\perp} / (r_L v) \sim 0.3$ for Kolmogorov turbulence with $\eta = 0.5$ and χ between 0.05 and 0.4, we find that

$$\tau_{\text{diff}} \lesssim \frac{5H^2}{3r_L v_X} = 9\epsilon \text{ Gyr} \left(\frac{H}{300 \text{ pc}} \right)^2 \left(\frac{m_X}{10^6 \text{ TeV}} \right)^{-1} \times \left(\frac{v_X}{150 \text{ km s}^{-1}} \right)^{-2} \left(\frac{B}{5 \mu\text{G}} \right). \quad (2)$$

Therefore, the present configuration and strength of the Galactic magnetic field can prevent diffusion of (unaccelerated) CHAMPs across the Galactic disk in the life time of the disk for mass particles $m_X < 10^6 \epsilon$ TeV. The corresponding gyroradius for a mass of $10^6 \epsilon$ TeV moving at 150 km s^{-1} in a field of $5 \mu\text{G}$ is 0.1 pc .

It is likely that CHAMPs are accelerated to much higher velocities by supernova shocks. The inclusion of this effect would give a more constraining upper limit on m_X .

3. ENERGY LOSS OF CHAMPs IN THE DISK

In the preceding section we have seen that halo CHAMPs with masses $m_X < 10^6 \epsilon$ may have difficulty penetrating the magnetized Galactic disk, whereas those inside it stay confined to the disk. Trapped particles in the disk gain energy through electrostatic fields, Fermi acceleration in shock waves, and its descendants (e.g., Blandford 1994), and loss kinetic energy due to Coulomb scatterings with electrons and protons of the diffuse interstellar gas. The dissipation timescale is $\tau_{\text{dis}} = E / |\dot{E}|$, with $E = mv_X^2/2$ and

$$|\dot{E}| = 4\pi n_e \frac{\epsilon^2 e^4}{m_e v_X} \ln \Lambda, \quad (3)$$

where n_e is the electron density ($\approx 0.025 \text{ cm}^{-3}$ in the solar vicinity) and the Coulomb logarithm has a value of about 20. CHAMPs may avoid strong cooling if the dissipation timescale τ_{dis} for CHAMPs trapped on the disk be greater than the shock acceleration timescale τ_{acc} . Since $\tau_{\text{acc}} \gtrsim 0.01 \text{ Gyr}$, the condition $2\tau_{\text{cool}} > \tau_{\text{acc}} = 0.01 \text{ Gyr}$ implies

$$m_X > 2 \times 10^3 \epsilon^2 \text{ TeV} \left(\frac{v_X}{150 \text{ km s}^{-1}} \right)^{-3}. \quad (4)$$

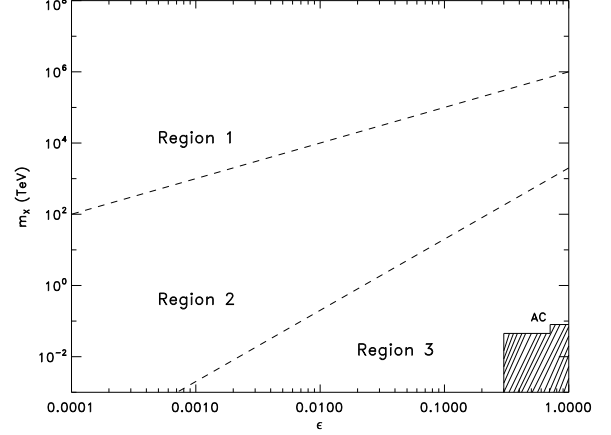


FIG. 2.— Regions of mass-charge space of astrophysical relevance. Halo milli-charged particles in region “1” have no difficulty in penetrating the disk, whereas CHAMPs in region “3” would interact strongly with the baryonic matter in the disk resulting in strong observable consequences, unless its abundance is very tiny. For reference, the excluded region from accelerator experiments (AC) after Davidson et al. (2000), is also shown.

This constraint is valid for any value of ϵ provided that m_X is larger than the electron mass $m_e \sim 0.5 \text{ MeV}$. We will not consider the regime $m_X < m_e$ because they are excluded for $10^{-15} \lesssim \epsilon < 1$ (Davidson et al. 2000). In Fig. 2 we plot the region of mass-charge space for CHAMPs, combining the constraint derived in §2 and Eq. (4). CHAMPs in region “2” can be suspended in the halo without penetrating the disk and may be very evasive for direct terrestrial detection because the flux of CHAMPs reaching Earth may be highly suppressed. If CHAMPs are thermal relics, they must also satisfy the unitary bound $m_X \lesssim 120 \text{ TeV}$ (Griest & Kamionkowski 1990). Combining this constraint with Eq. (4), we find $\epsilon < 0.2$ for thermal relics.

4. THE GLOBAL MAGNETIC SUPPORT

For simplicity, let us assume for a moment that the Galactic magnetic field is horizontal. As depicted in Fig. 1, CHAMPs with $m_X < 1 \times 10^6 \epsilon$ TeV execute approximately half a gyro-orbit before finding themselves back in the unmagnetized region and with velocities directed away from the magnetized region. This leads to the plasma being excluded from the magnetized disk. In the boundary layer, a current layer develops as a result of a thermal, unmagnetized plasma interacting with a magnetized region. It is a classical result that the (kinetic) motions of individual particles in collisionless plasmas can be reconciled with the role inferred for the pressure in MHD (e.g., King & Newmann 1967; Cravens 1997). For example, in a boundary layer like the terrestrial magnetopause, the thermal (or kinetic) pressure of the solar wind is balanced by the pressure of the terrestrial magnetic field and this separates the interplanetary magnetic field from the magnetospheric cavity.

Suppose that CHAMPs cannot penetrate down to $z = Z_{\min}$ because of the Galactic magnetic barrier (see §2). Since CHAMPs are essentially collisionless, the magnetic field is the only agent that may support the weight of the CHAMPs in the halo. Integrating the equation of vertical equilibrium from $z = Z_{\min}$ to $z = \infty$, assuming zero pressure at $z = \infty$, and ignoring the weight of coronal gas, we find

$$P_B(Z_{\min}) \gtrsim \int_{Z_{\min}}^{\infty} \rho_{ch} K_z dz, \quad (5)$$

where P_B is the magnetic pressure, $\rho_{ch}(z)$ the mass density of

CHAMPs and K_z the vertical positive gravitational acceleration. For a spherical dark halo, the contribution of CHAMPs to the weight term at the solar vicinity is

$$\int_{Z_{\min}}^{\infty} \rho_{ch} K_z dz = f \rho_X v_X^2 = 1.7 f \times 10^{-10} \text{ dyn cm}^{-2} \times \left(\frac{\rho_X}{0.01 \text{ M}_{\odot} \text{ pc}^{-3}} \right) \left(\frac{v_X}{150 \text{ km s}^{-1}} \right)^2, \quad (6)$$

where f is defined as the mass fraction of dark matter in CHAMPs. The weight of the CHAMPs produces a confinement effect. Interestingly, the observed synchrotron emission above the plane in the solar neighbourhood implies that the scale height of the magnetic field is greater than what would be inferred from the weight distribution of the interstellar matter (e.g., Cox 2005). By requiring that the confinement of the magnetic pressure is entirely due to the weight of the CHAMPs, an upper value on the abundance of CHAMPs can be derived.

The observed synchrotron emission above the plane in the solar neighbourhood indicates that the total magnetic field strength is $2\text{--}5 \mu\text{G}$ at a height of $z = 1 \text{ kpc}$ (Ferrière 2001; Cox 2005; Gaensler et al. 2008). If we identify Z_{\min} as the HWHM of the magnetoionic disk $\sim 1 \text{ kpc}$ (e.g., Kalberla 2003) and by equating the magnetic pressure at $z = Z_{\min} \approx 1 \text{ kpc}$ with the weight term, we obtain the desired constraint on f , once adopting the highest magnetic value of $5 \mu\text{G}$ allowed by observations:

$$f \leq 7 \times 10^{-3} \left(\frac{\rho_{X,\odot}}{0.01 \text{ M}_{\odot} \text{ pc}^{-3}} \right)^{-1} \left(\frac{v_X}{150 \text{ km s}^{-1}} \right)^{-2}. \quad (7)$$

This constraint is independent of charge e . This estimate is very robust to the precise value adopted for Z_{\min} because the magnetic field decays very slowly with z .

In our derivation, we have assumed that the halo is spherical. Consider now an oblate isothermal dark halo with axis ratio q :

$$\rho_X(R, z) = \frac{v_c^2}{4\pi G \alpha q} \left(R^2 + \frac{z^2}{q^2} \right)^{-1}, \quad (8)$$

where v_c is the asymptotic circular velocity at the equatorial plane and $\alpha = \gamma^{-1} \arcsin \gamma$, with $\gamma = \sqrt{1 - q^2}$. In this model, the velocity dispersion is given, within less than 10%, by $v_X \simeq 1.16 \sqrt{q} (v_c / \sqrt{2})$, for flattening $0.05 < q < 0.5$ (e.g. Gerhard & Silk 1996). Even though the velocity dispersion for $q < 1$ is smaller than in the spherical case, the weight term changes only by $\sim 10\%$ as compared to the spherical case, even for rather flattened halos ($q \approx 0.5$).

So far, it was assumed that CHAMPs and neutraCHAMPs are well mixed. Now, we relax that assumption and search for the distributions of neutraCHAMPs and CHAMPs that allow to have the largest mass in CHAMPs. This occurs when CHAMPs have an almost zero vertical dispersion and settle on to layers of negligible thickness at $|z| = Z_{\min}$, but neutraCHAMPs populate a spherical halo. The vertical density profile of CHAMPs is then $\rho_{ch}(z) = \Sigma_{ch} \delta(|z| - Z_{\min})/2$, where Σ_{ch} is the surface density of CHAMPs at $R = R_{\odot}$. From Eq. (5), we obtain that $P_B \gtrsim \Sigma_{ch} K_z/2$ at $z = Z_{\min}$. Taking $K_z \approx 6 \times 10^{-9} \text{ cm s}^{-2}$ at $z = 1 \text{ kpc}$ (e.g., Holmberg & Flynn 2004), we find $\Sigma_{ch} < 6 \text{ M}_{\odot} \text{ pc}^{-2}$ or, equivalently, $f \approx \Sigma_{ch}/(2\rho_{X,\odot} R_{\odot}) \lesssim 3.5 \times 10^{-2}$. However, it is difficult to justify this additional degree of freedom in the model until a non-gravitational mechanism for so efficiently dissipation of CHAMP's energy is satisfactorily established. In addition, it is likely that Parker instabilities will

destroy these cold layers of CHAMPs if they are sustained against gravity by magnetic fields.

Consider now a portion of the disk at larger galactocentric distances, say $R = 2R_{\odot}$. Following the same procedure than in the solar neighbourhood, we need to estimate the total magnetic pressure at $(2R_{\odot}, Z_{\min})$, which should be responsible to give support to the halo CHAMPs. The large-scale magnetic field may have a scaleheight 5–10 times the scaleheight of the neutral gas disk, so that we may assume that $B_0(Z_{\min}) \simeq B_0(z = 0)$. The random magnetic field is expected to be roughly in equipartition with the kinetic energy in the turbulence. Therefore, its vertical scaleheight should be similar to that of the gas. If magnetic fields are still a barrier for halo CHAMPs, then we may assume that $Z_{\min} > H$ and, consequently, the magnetic pressure by the random component at Z_{\min} is less than 10% the pressure by the random field at $z = 0$. Collecting both contributions, we derive an upper limit for the total magnetic pressure at Z_{\min} :

$$P_B < \frac{B_0^2 + 0.1b^2}{8\pi} = \frac{B_0^2}{8\pi} (1 + 0.1\alpha), \quad (9)$$

where $\alpha \equiv b^2/B_0^2$, with b^2 and B_0^2 evaluated at $z = 0$. The ordered magnetic field is difficult to measure in the outer Galaxy, but there is evidence that it decays with radius R as a power-law between R^{-1} and R^{-2} , probably as $\exp(-R/R_B)$ with $R_B = 8.5 \text{ kpc}$ (Heiles 1996; Han et al. 2006). The uniform magnetic field in the solar neighbourhood is $2\text{--}4 \mu\text{G}$, depending on the authors (Beck 2002; Han et al. 2006). If we generously take a value in the solar circle of $4 \mu\text{G}$ we infer a strength $B_0 \sim 1.5 \mu\text{G}$ at $2R_{\odot}$. Assuming a spherical dark halo with a mass density at $2R_{\odot}$ of $\sim \rho_{X,\odot}/4$, then $\int \rho_{ch} K_z dz = f \rho_{X,\odot} v_X^2/4$. At $2R_{\odot}$, our assumption that the halo is spherical is a very good approximation (e.g., Belokurov et al. 2006; Fellhauer et al. 2006). By imposing pressure balance at $z = Z_{\min}$ (Eq. 5), the following constraint for f is inferred

$$f \leq 2 \times 10^{-3} (1 + 0.1\alpha) \left(\frac{\rho_{X,\odot}/4}{0.0025 \text{ M}_{\odot} \text{ pc}^{-3}} \right)^{-1} \left(\frac{v_X}{150 \text{ km s}^{-1}} \right)^{-2}. \quad (10)$$

Other observational estimates assure our generously-taken magnetic intense. In fact, data from rotation measurements of pulsars suggest uniform magnetic fields of $\sim 0.7 \mu\text{G}$ at $R = 2R_{\odot}$ (Rand & Lyne 1994), which coincides with the extrapolation of the fit of radial variation of the regular field by Han et al. (2006).

Beyond $2R_{\odot}$ it is uncertain if supernovae shocks are able to clean the disk from CHAMPs. It might be also possible that beyond the optical radius, the magnetic field is too weak to prevent CHAMPs from crossing the disk, but any more complicated analysis is useless in the face of such ignorance. We conclude that charged particles can be suspended in the halo, so that they would be impossible to detect as they never reach the Earth. However, the mass fraction of bare CHAMPs in the halo must be rather small $f \lesssim (2\text{--}7) \times 10^{-3}$. In a X^+X^- symmetric Universe, neutraCHAMPs may compose a fraction $< (2\text{--}7) \times 10^{-2}$, because the ratio of their relative abundances may be as much as 10:1 (Dimopoulos et al. 1990). Therefore, CHAMP models require three ingredients: neutraCHAMPs, CHAMPs and neutral dark matter. One possibility is that $f \approx 0.5$ ¹ at early times and CHAMPs decay to neutral dark matter with a lifetime $< 2.75 \text{ Gyr}$ to reach $f \sim 3 \times 10^{-3}$ at present.

¹ We adopt $f = 0.5$ because positive CHAMPs and neutraCHAMPs are expected to be approximately in equal numbers.

5. DISCUSSION

5.1. *The origin of cores in galaxies*

Our upper limit on f rules out CHAMPs as an explanation for the formation of constant density cores in dark matter halos. The reduction of the central density after they have driven the formation of galactic halos would be insignificant. Even if all the CHAMPs were depleted from the central parts of the galaxies, the rotation velocity in a certain galaxy would suffer a negligible change of $(0.1 - 0.35)\%$ for $f \sim (2 - 7) \times 10^{-3}$. If CHAMPs decay to neutral particles, f was larger in the past. In such scenario, the formation of cores may result from the evacuation of CHAMPs in the central regions of galaxies by supernova shocks, provided that the decay times $\gtrsim 1.5$ Gyr. Combined with the constraint that the decay times < 2.75 Gyr, discussed in our previous section, a fine-tuning of the decay time is required.

5.2. *Ram pressure stripping and collisions of galaxy clusters*

Magnetic fields couple CHAMPs with themselves and with ordinary matter. This coupling might cause ram pressure stripping of both baryonic and dark matter of subhalos and satellite systems. Consider, for instance, the collision of two galaxy clusters. Estimates for the magnetic field strength in clusters range from roughly $1 - 10 \mu\text{G}$ at the center and $0.1 - 1 \mu\text{G}$ at a radius of 1 Mpc, values that correspond to a plasma beta for the CHAMPs, $\beta \equiv 8\pi P_{th}/B^2 \approx 2f \times 10^{3-4}$, a hot plasma. Even in this dynamically weak magnetic field, the mean gyroradius for a CHAMP with $m_x = 10^6 e$ TeV, is $\lesssim 5$ pc at the center and $\lesssim 50$ pc at 1 Mpc. The governing equations of collisionless hot plasmas were developed by Chew et al. (1956), whose theory is known as the Chew-Goldberger-Low approximation. This approximation, which leads to MHD equations with anisotropic pressure, is satisfactory when the Larmor frequency is large compared to other characteristic frequencies of the problem and the mean particle gyroradius is short compared to the distance over which all the macroscopic quantities change appreciably (e.g., Spitzer 1962; Schmidt 1966). Therefore, charged massive particles in the halo of galaxy clusters can be described in the fluid-like anisotropic MHD approximation; in the merger process, they would behave as a clump of fluid, experiencing ram pressure stripping and drag deceleration similar to the gas component. Since CHAMPs should be attached to the gas component, the

observed offset between the centroid of dark matter and the collisional gas of the subcluster in the Bullet Cluster implies $f \ll 1$ (e.g., Natarajan et al. 2002; Markevitch et al. 2004). Although the current lensing data accuracy is not sufficient to derive the mass distribution of the subcluster in the Bullet Cluster, the derived mass estimates of the subcluster leave little room for dark matter in the gas bullet.

Galactic halo CHAMPs may also exert ram pressure on the gas component of the LMC and its stream due to their continuous scattering by the intrinsic magnetic field of the LMC and the Magellanic stream. For a Milky Way-type halo of $\sim 10^{12} M_\odot$, a fraction f of 3×10^{-3} implies that the mass in CHAMPs could be up to $\sim 3 \times 10^9 M_\odot$ and the density at 50 kpc of $0.9 \times 10^{-6} M_\odot \text{pc}^{-3}$. Since these values are smaller than those required to explain the mass and extension of the Magellanic Stream and the size and morphology of the gaseous disk of LMC (Mastropietro et al. 2005), we cannot reduce any further our upper limit on f with the current observations of the LMC disk and the Magellanic Stream.

6. CONCLUSIONS

Whilst the common wisdom holds that dark matter is neutral and collisionless, it is important to explore the possibility of it having nonzero, not necessarily integer, charge. We have considered the pressure support of CHAMPs in our Galaxy to derive a simple, upper limit on the fraction of CHAMPs and milliCHAMPs, $f \lesssim (2 - 7) \times 10^{-3}$. If f was roughly constant over time, this constraint rules out CHAMPs as the origin of the cores in LSB and dwarf galaxies. In the range of astrophysical interest, CHAMPs behave like strongly interacting (fluid-like) dark matter (SIDM). Thus, they face many of the problems attributed to SIDM. As some examples, we have discussed the survival of the Magellanic Stream and the mass distribution of the Bullet Cluster. Our constraint that the mass in CHAMPs in the Galaxy is not larger than the mass of coronal gas in the halo seems to apply also to galaxy clusters.

We are indebted to Leonid Chuzhoy for valuable comments which led to significant improvements in the manuscript. We are grateful to Julio Martinell for many important discussions. F.J.S.S. acknowledges financial support from PAPIIT project IN114107 and CONACyT 2006-60526. E.M.G. thanks support from DGAPA-UNAM postdoctoral fellowship.

REFERENCES

- Barwick, S. W., Price, P. B., & Snowden-Ifft, D. P. 1990, *Phys. Review Lett.*, 64, 2859
- Beck R. 2002, in *The Astrophysics of Galactic Cosmic Rays*, eds. R. Diel et al. (Kluwer, Dordrecht, The Netherlands)
- Belokurov, V., et al. 2006, *ApJ*, 642, L137
- Berger, C. F., Covi, L., Kraml, S., & Palorini, F. 2008, *JCAP*, 10, 005
- Blandford, R. D. 1994, *ApJSS*, 90, 515
- Casse, F., Lemoine, M., & Pelletier, G. 2002, *Phys. Review D*, 65, 3002
- Chew, G. F., Goldberger, M. L., & Low, F. E. 1956, *Proc. Roy. Soc.*, A236, 112
- Chivukula, S. R., Cohen, A. G., Dimopoulos, S., & Walker, T. P. 1990, *Phys. Review Lett.*, 65, 957
- Chuzhoy, L., & Kolb, E. W. 2008, *arXiv: 0809.0436*
- Cox, D. P. 2005, *ARA&A*, 43, 337
- Cravens, T. E. 1997, *Physics of Solar System Plasmas* (Cambridge University Press)
- Davidson, S., Hannestad, S., & Raffelt, G. 2000, *Journal of High Energy Physics*, 05, 003
- De Rújula, A., Glashow, S. L., & Sarid, U. 1990, *Nucl. Phys. B*, 333, 173
- Dimopoulos, S., Eichler, D., Esmailzadeh, R., & Starkman, G. D. 1990, *Phys. Review D*, 41, 2388
- Fellahauer, M. et al. 2006, *ApJ*, 651, 167
- Ferrière, K. M. 2001, *Rev. Mod. Phys.*, 73, 1031
- Fletcher, A., & Shukurov, A. 2001, *MNRAS*, 325, 312
- Gaensler, B. M., Madsen, G. J., Chatterjee, S., & Mao, S. A., *PASA*, in press (*arXiv:0808.2550*)
- Gerhard, O., & Silk, J. 1996, *ApJ*, 472, 34
- Giacalone, J., & Jokipii, J. R. 1999, *ApJ*, 520, 204
- Gould, A., Draine, B. T., Romani, R. W., & Nussinov, S. 1990, *Phys. Lett. B*, 238, 337
- Griest, K., & Kamionkowski, M. 1990, *Phys. Review Lett.*, 64, 615
- Han, J. L., Manchester, R. N., Lyne, A. G., Qiao, G. J., & van Straten, W. 2006, *ApJ*, 642, 868
- Heiles, C. 1996, in *ASP Conf. Ser. 97, Polarimetry of the Interstellar Medium*, ed. W. Roberge & D. Whittet (San Francisco: ASP), 457
- Holmberg, J., & Flynn, C. 2004, *MNRAS*, 352, 440
- Kalberla, P. M. W. 2003, *ApJ*, 588, 805
- Kallenrode, M.-B. 1998, *Space Physics. An introduction to plasmas and particles in the heliosphere and magnetospheres*, 1st Edition (Springer-Verlag)
- King, J. W. & Newman, W. S. 1967, *Solar-terrestrial physics* (Academic Press, London)

- Markevitch, M. et al. 2004, ApJ, 606, 819
- Mastropietro, C., Moore, B., Mayer, L., Wadsley, J., & Stadel, J. 2005, MNRAS, 363, 509
- Natarajan, P., Loeb, A., Kneib, J.-P., & Smail, I. 2002, ApJ, 580, L17
- Parks, G. K. 1991, Physics of Space Plasmas. An Introduction, 1st Edition (Addison-Wesley Publ.)
- Perl, M. L., et al. 2001, Int. J. Mod. Phys. A 16, 2137
- Rand, R. J., & Lyne, A. G. 1994, MNRAS, 268, 497
- Schmidt, G. 1966, Physics of High Temperature Plasmas (Academic Press, New York and London)
- Spitzer, L. Jr 1962, Physics of Fully Ionized Gases, 2nd Edition, Interscience Publ. (New York: Wiley)
- Taoso, M., Bertone, G., & Masiero, A. 2008, JCAP, 03, 022
- Verlerk, P., et al. 1992, Phys. Review Lett., 68, 1116